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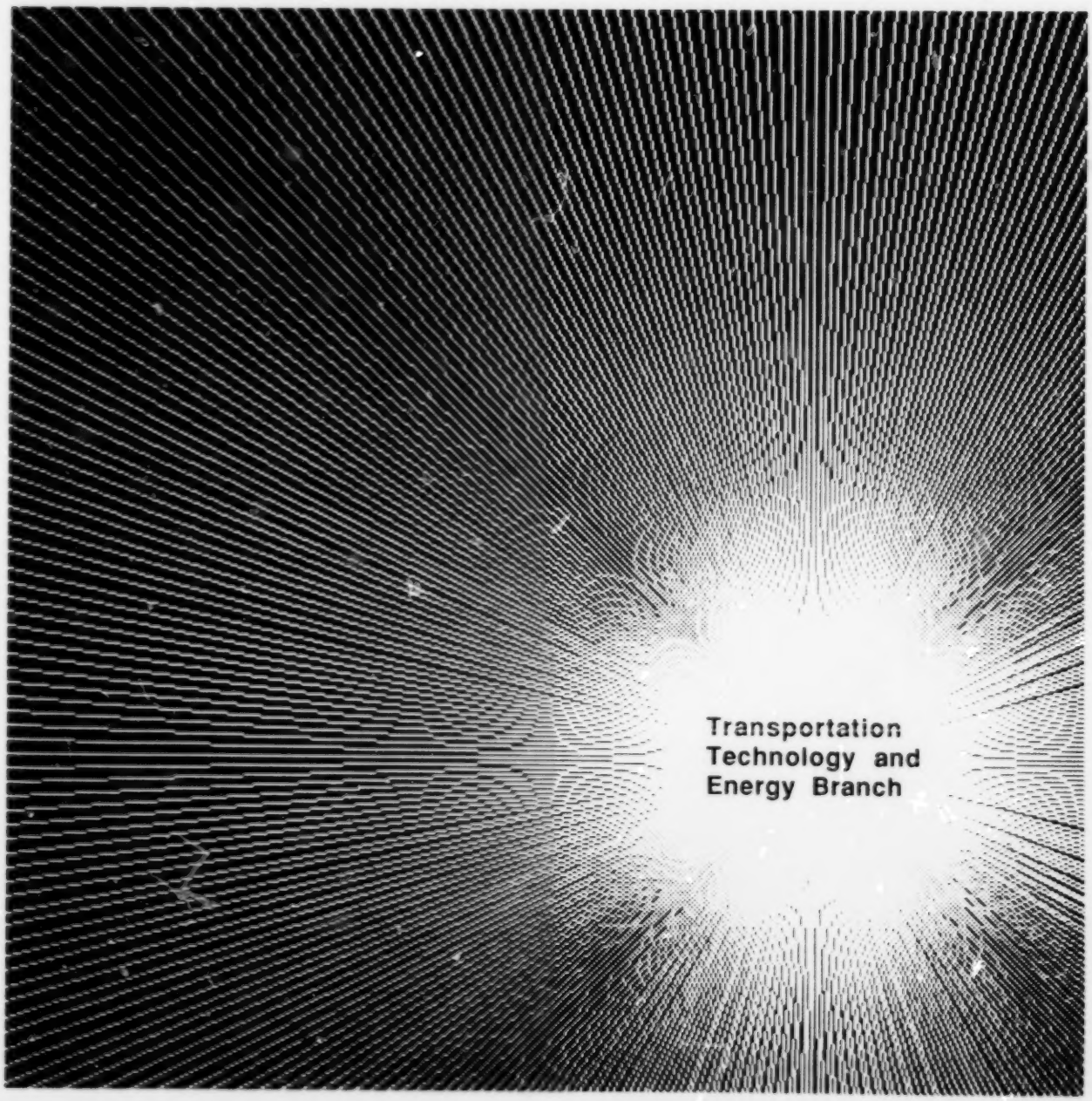

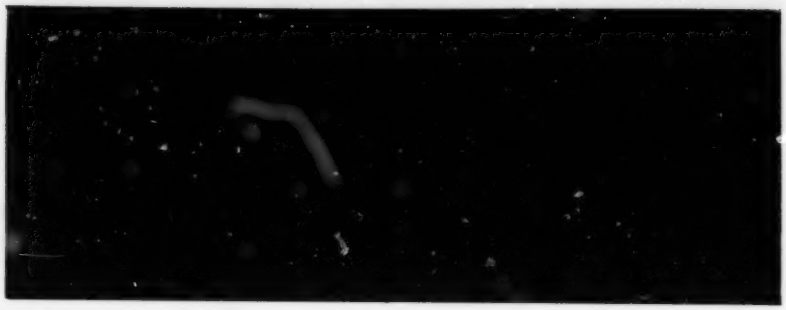

# Field Testing of a Prototype Vision System for Rail Profile Measurement

RT-91-02

# Technical Report Documentation Page

## Field Testing of a Prototype Vision System for Rail Profile Measurement

Prepared by: D. Leung

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Abstract: A prototype vision system for measuring rail profiles was tested on a section of the TTC subway system. The measurements made with the vision system were compared to those manually obtained by TTC using a conventional profilometer.

The report presents the vision-based and manual measurement data and the associated findings and concludes that the vision-based measurements compared very well with the manual counterpart in accuracy.

Recommendations are also made regarding future work.

Key words: Machine vision, image processing, automation, rail profiles, profile measurement, rail maintenanc, planning, rail wear

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# Field Testing of a Prototype Vision System for Rail Profile Measurement

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## 1/ INTRODUCTION

In 1988 the Rail and Advanced Transportation Systems Office conducted a test program in which the RIMS (Rail Inspection and Measurement System), a prototype optical rail profile measurement system that had originally been designed for demonstration use in a stationary indoor environment, was tested on a section of test track for the following performance criteria:

- repeatability of measurements,
- consistency in performance, and
- accuracy.

The findings of that program led to the conclusion that the RIMS performed well in regard to the above criteria under adequate lighting conditions, and that the performance and capabilities of the existing design could benefit tremendously from a few improvements [1]. It was also concluded that the system should be tested further in a field environment in order to subject it to all feasible physical and operational conditions that would normally be encountered during production service [2].

Two sets of field tests were subsequently performed at night-time, jointly with the Toronto Transit Commission, on the Bloor line of its subway system. This report contains the results of these field tests.

## 2/ TEST OBJECTIVES

The field testing program was performed with the following objectives:

- To test the physical integrity of the prototype vision system under actual field conditions;

- To test all aspects of the performance, including accuracy and consistency, of the prototype vision system under actual field conditions;

- To gather more experience in the use of the vision system.

## 3/ TEST SET-UP

The test set-up consisted of the RIMS installed on a mobile aluminum carriage for operation on tracks.

The RIMS consists of three major components: a sensor, a 80286-based first-generation Compaq portable personal computer with a 20-MB hard disk drive, and a video monitor. Figure 1 shows a conceptual set-up of the RIMS.

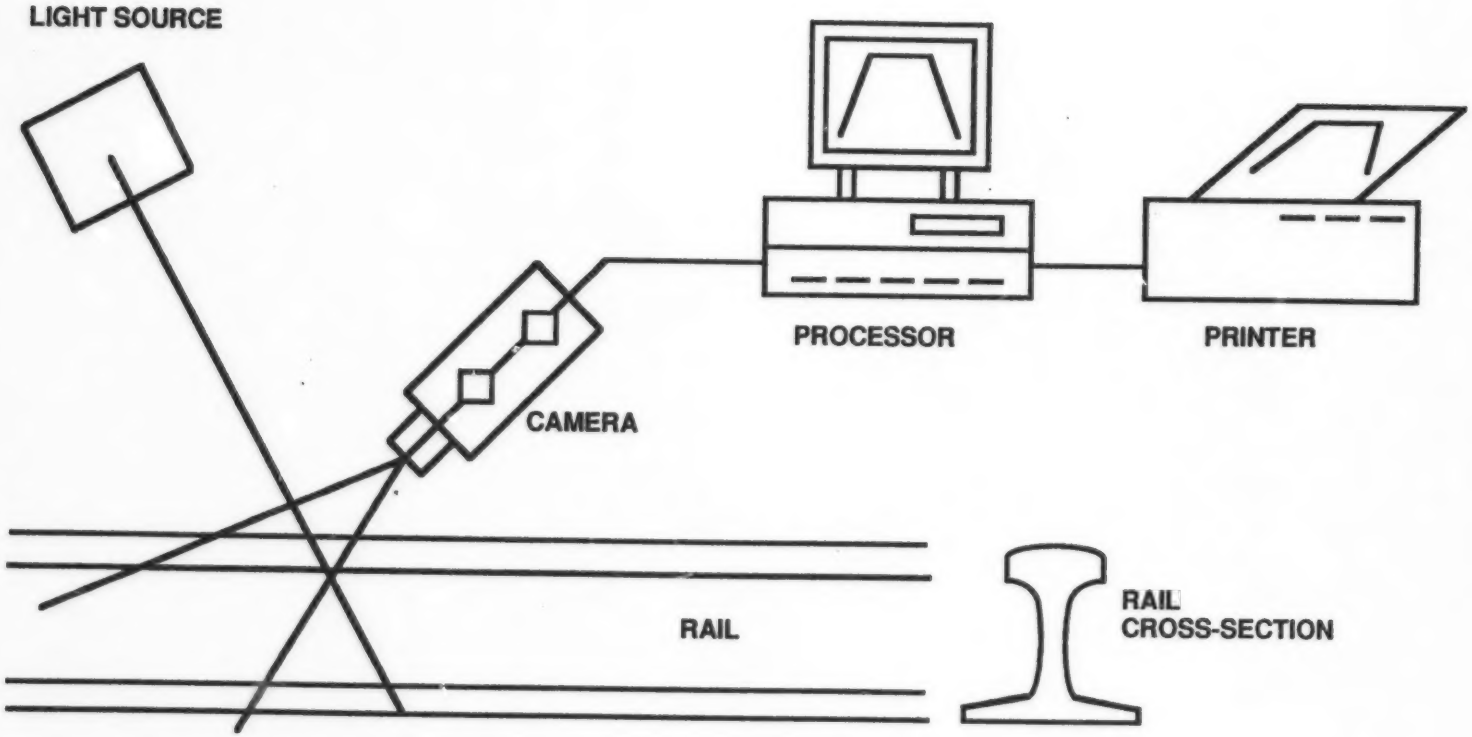


Figure 1/ A Conceptual Set-up of the RIMS

The sensor employs a simple 100 W, 12 V DC incandescent light source and a single video camera. Lenses and mirrors allow the sensor to "look" at both the field and gauge sides of the railhead. The camera has a resolution of 512 (vertical) x 384 (horizontal). With a design field view of about 5 x 5 inches, the image resoiution achievable by this sensor is about 0.013 inch while actual measurement accuracy is estimated at about 0.020 inch. Figure 2 shows a schematic layout of the RIMS, while Figure 3 shows the sensor as installed on the aluminum carriage.

The computer is equipped with commercially available image processing boards that serve to capture the image of the rail profile as detected by the camera, digitize it, and store the digital data on the hard disk of the computer. The computer also allows digitized profiles to be displayed on the built-in monitor, or on the separate analogue monitor. The latter is primarily used for a live display of the rail profiles that are being measured.

Processing of the image data is performed by software. This can be carried out in real time, or the data can be stored for later "off-line" processing. Wear calculations consist of the railhead wear, defined as the reduction in the height of the railhead as measured along the vertical centre-line of the rail section, and the gauge wear, defined as the reduction in the width of the railhead as measured at the gauge level of the rail section. Both wear parameters are with respect to a new nominal rail section.

Further details of the RIMS can be found in the paper, "Application of Machine Vision to Wheel/Rail Maintenance [1]."

## 4/ TEST DESCRIPTION

The westbound subway track section between the Sherbourne and Yonge stations was selected to be the test site. The track section consists of a moderately curved section starting from the west side of the Sherbourne station and continuing into a tangent section towards the Yonge station. The curve section exhibited a number of varied wear patterns over a relatively small distance. Shelling was evident on some lengths of this section. Illumination in the tunnel was sufficient to allow the test crew to operate without the aid of auxiliary lighting.

Two separate sets of tests were performed: the first in November 1988, and the second in April 1989.

### Test Set 1

The primary objective of this test set was to pick up measurements on the fly, as one would in the field, under relatively uncontrolled field conditions. This was achieved by having the test engineer sit on the carriage to operate the vision system while the carriage was pushed along at a moderate-to-fast walking pace.

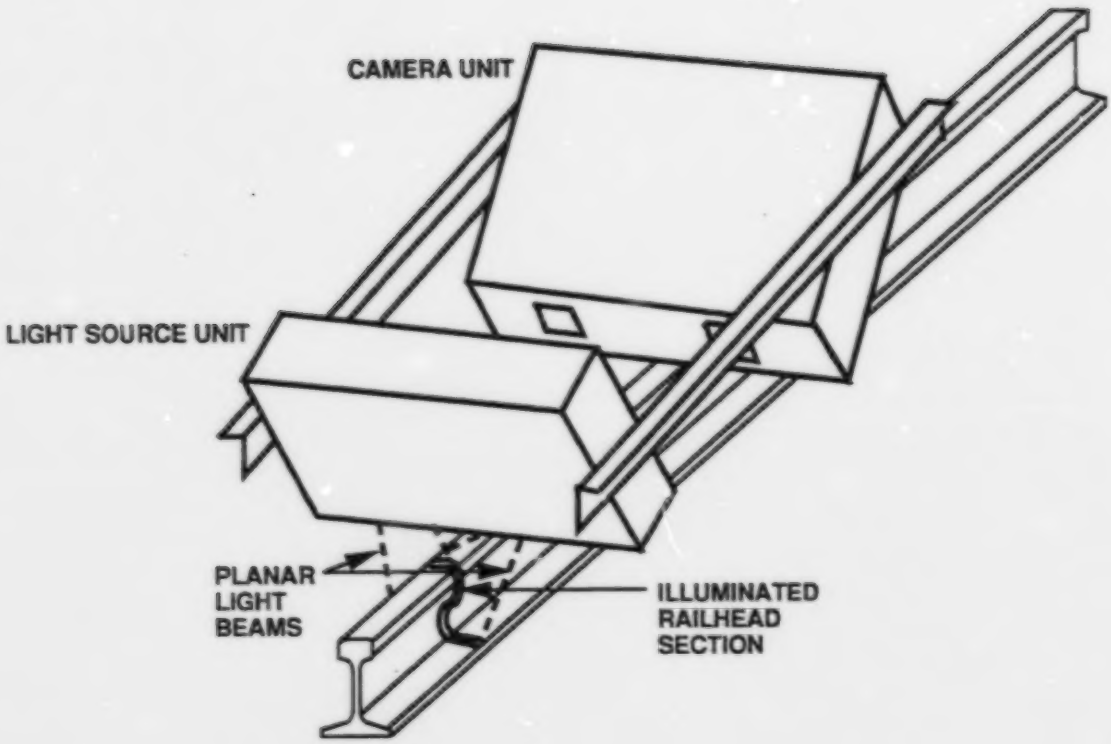


**Figure 2/ Layout of the RIMS**

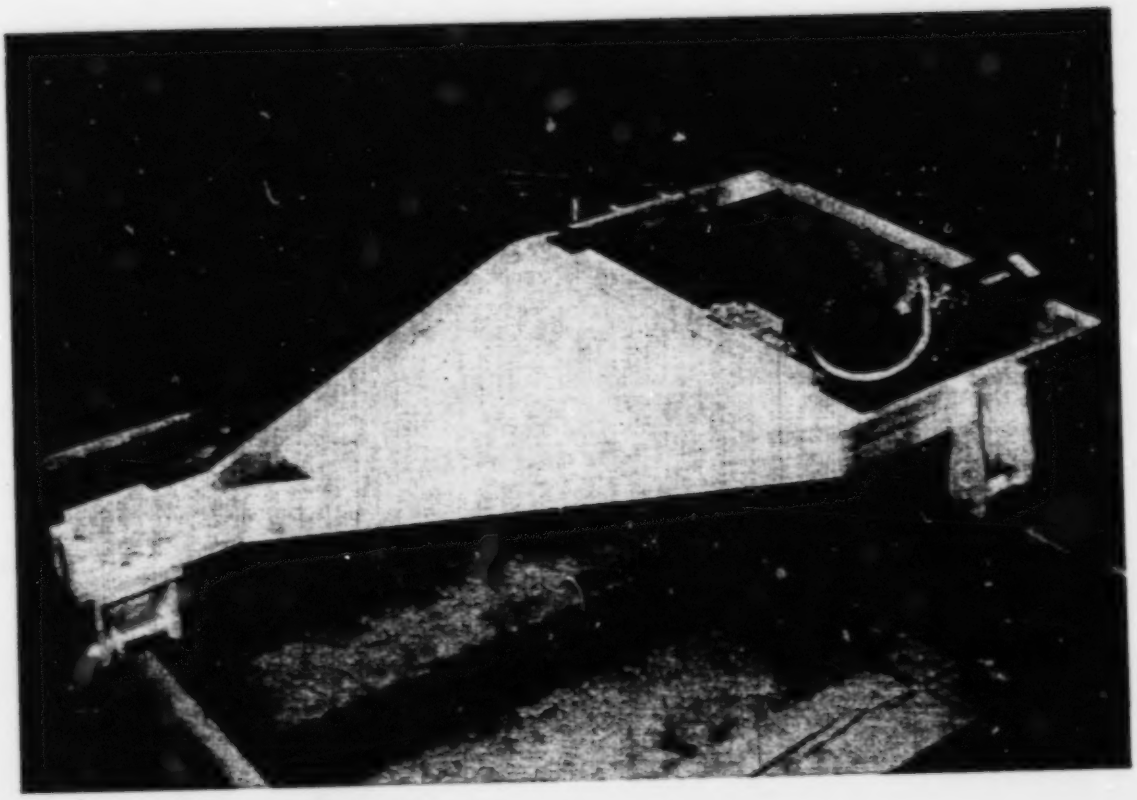

**Figure 3/ Actual Test Set-up**

The RIMS and the carriage were loaded onto a work car at the Greenwood carhouse for transport to the test site, where they were quickly unloaded and positioned on the tracks. The portable computer, analogue monitor, and a printer were all placed on the triangular portion of the carriage. The flange clearance of the wheels was set at about 1/2 inch to allow the carriage to skew as much as a real rail truck would. Owing to delays in setting out from the Greenwood carhouse, a time window of only about 1 1/4 hours was available for the tests. The actual time available for taking measurements was further reduced by the need to re-route the power cord to the next available AC power outlet, thereby making it necessary to re-boot the computer and re-load the imaging program at several intervals.

A few sample measurements were taken before commencing the tests. It was found that the aluminum frame supporting the sensor appeared to have been twisted during transport, thereby producing a conspicuous vertical split near the centre of the rail profile. This was attributed to the fact that the frame had not been designed to withstand any twisting that might result from rough handling: it is made of only two aluminum angles attached to the sides of the cabinets that house the camera and the light source. The RIMS was crudely re-aligned by shimming the aluminum frame until the two halves of the rail profile appeared to be properly aligned. Otherwise, the quality of the images as seen on the analogue monitor was generally good.

Image capture was set in a mode whereby measurements would be taken in response to the operator's prompt. Wear calculations were performed "on-line" between measurements. This was mainly for the purpose of ensuring that the system was performing properly. Owing to the very limited time window, measurements were taken of the high rail only. The total length of the track section over which measurements were actually made was about 700 feet, and this included all of the curve section and part of the tangent section.

A total of 69 measurements were taken of the high rail at roughly 10-foot intervals; these included about a dozen measurements made at marked locations where manual measurements would be made later by TTC for comparison. Several typical profiles, along with their corresponding wear measurements, are shown in Appendix I.

**Test Set 2**

TTC reported very good agreement between the vision-based and manual measurements obtained for Test Set 1. Therefore the objective of this test set was, at TTC's request, to re-affirm the capability of the RIMS by taking a closer look at its accuracy and reliability in comparison to manual measurements, and thereby reinforce confidence in the potential of using vision-based automation in rail wear monitoring.

The same equipment was used as in the November 1988 tests. A total of 35 locations were marked, at 50-foot intervals, on the track section to be measured. (This interval corresponds to the interval at which TTC would normally make selective profile

measurements.) Only about 45 minutes was made available for conducting this test set.

Again, it was found that the aluminum frame was somewhat twisted as had been experienced during Test Set 1. However, efforts to attempt to re-align the sensor by shimming were not as successful as during Test Set 1, since the shims were constantly jolted out of position as the carriage was pushed over the welded rail joints. In view of the limited time that was available, and the fact that the misalignment appeared to cause a conspicuous split of the rail profiles only near the centre of view, which may or may not create any errors in calculating the head wear depending on the location of the rail's centre-line relative to the centre of view, it was decided to live with the misalignment and make appropriate adjustments afterwards.

In view of the limited time available, only 12 measurements each were made on the low rail and the high rail, resulting in a total of 24 measurements. Several of which are shown in Appendix II. It is noted that some of the measurements were made on locations with restraining rails, without any difficulty. For comparison, 24 manual measurements were also made at the same test locations by TTC.

## 5/ TEST OBSERVATIONS

During the first test set, which was conducted in November 1988, the RIMS appeared to have held up very well against the rather rough handling that it was subjected to during loading and unloading, and against the rough ride on the tracks (the sensor and the computer were visibly bouncing up and down when the carriage was pushed over the welded rail joints). Distortion of the supporting frame apparently became more serious during the second test set, conducted five months later, such that more effort was needed to temporarily re-align the sensor, which would still have been achievable had not the time window available for testing been so limited.

A careful examination of the recorded profiles from Test Set 1 revealed some interesting observations:

1/ The profiles appear to exhibit several varied wear patterns, including, in sectional view, concave wear. This is quite reflective of the actual wear patterns that were witnessed of the measured rail sections. The transition from one pattern to another appeared to correspond to changes in the radius of curvature of the rails.

2/ Shelling was exhibited by some rail lengths, and this seemed to be reflected in the recorded profiles by the "mushiness" of the data as opposed to the "clean" lines exhibited by rails that did not have shelling.

The rail profiles from Test Set 2 invariably showed a conspicuous split at the centre of the field of view, with the left-hand side (which was the field side) portion of the image situated slightly higher than the right-hand side (which was the gauge side) portion.

Most of these profiles were somewhat off to the left-hand side of the field of view. Since the railhead wear was measured at the centre line of the image, no errors in the railhead wear measurement would result for these profiles. For the remaining half dozen profiles that were somewhat off to the right-hand side of the field of view, the misalignment would introduce a small error in the railhead wear value.

## 6/ MANUAL MEASUREMENTS

For each of the test locations marked for comparison in both of the test sets, measurements were taken by TTC using a conventional profilometer. This device generates a trace of the rail profile, onto which a template for a standard unworn rail section can then be superimposed. The differences between the standard profile and the as-traced profile at prescribed locations, such as the rail top and the gauge point, are then measured. However, it was found that in a good number of cases, these differences could not be easily determined with reasonable accuracy because of an apparent lack of good match between the template and the as-traced profile; in these cases, subjective adjustments were needed. A few typical plots of the as-traced profiles, along with the standard profile superimposed on them, are shown in Appendix III.

## 7/ COMPARISON OF VISION-BASED AND MANUAL MEASUREMENTS

The RIMS measurements were compared against TTC's manual data for both sets of tests. TTC reported very good correlation between the manual measurements they made for Test Set 1 and the vision-based counterpart. However, the manual measurements have not been made available by TTC.

As for Test Set 2, the railhead wear and gauge wear as measured by the RIMS versus the corresponding quantities as measured manually by TTC, along with their differences, are shown in Table 1 and, graphically, in Figures 4a, 4b, 5a, and 5b.

For the railhead wear measurements, it can be noted from Table 1 that no more than eight of the test locations, namely, LR-B1, LR-B2, LR-B3, LR-B4, LR-C1, HR-B2, HR-C2, and HR-D5, show discrepancies that exceed 1/32 inch and of these eight discrepancies, only 6 exceed 1/16 inch. In terms of percentages, TTC found that 75% of the vision-based data showed less than 1/16" differences relative to the manual measurements, and 50% of the vision-based data showed less than 1/32" differences relative to the manual counterpart.

A careful examination of the profile plots for the six test locations noted in the above has shown that the apparently greater discrepancies at these locations are probably attributable to errors caused in the RIMS measurements by misalignment of the sensor (locations LR-B1, LR-B2, LR-B3, LR-B4, and LR-C1), or to errors in the manual result (such as at location HR-D5, where the profile plot suggests a greater railhead wear value than that reported by TTC). If adjustments were made to account for these errors, which were estimated to be in the order of 1/32 inch in the case of the

misaligned profiles, the RIMS-based and the manual measurements would show significant improvements in their comparison.

For the gauge wear results, Table 1 shows negative values, which imply "growth," for thirteen of the vision-based measurements. These negative values can be attributed to the effect of rust formations or dirt on the rail. In a manual measurements procedure, this effect would have been discounted or ignored. (In Figure 5b, which shows the differences between the RIMS-based and manual gauge wear measurements, the negative RIMS results have been set to zero.) Nevertheless, the magnitude of these values are by and large within the expected accuracy of about 1/32 inch of the vision system. Of the other eleven gauge wear measurements, only two (at stations HR-D2 and HR-D4) show discrepancies that exceed 1/16 inch while the rest exhibit discrepancies in the order of 1/32 inch.

A third parameter that was also used by TTC as a comparison criterion was the "percent railhead area loss" estimated on the basis of the measured values of railhead wear and gauge wear. This parameter was deemed more relevant to TTC's traditional means of assessing rail wear. Two sets of "percent railhead area loss" values, one based on the RIMS railhead and gauge measurements and the other on the manual counterparts, were calculated by TTC. These, along with their discrepancies, are tabulated as shown in Table 2, and plotted as shown in Figures 6a and 6b. These results show that about 30% of the measurements exhibited differences of less than 1% in the railhead area loss, about 58% showed differences of less than 3%, while the vast majority of the measurements, about 83%, showed differences of less than 5%.

Overall, it can be stated that there was very good agreement between the vision-based and manual measurements. In addition, it should be noted that the discrepancies described in the above between the RIMS and the TTC manual measurements are based on a comparison of results derived from two difference techniques of measurements, each of which is subject to certain inherent error bounds. These discrepancies should therefore not be viewed as deficiencies of the RIMS, but rather as a specific representation of the discrepancies that the RIMS, as it was configured at the time of the testing, exhibited relative to a set of measurements that were manually produced using relatively laborious techniques.

## 8/ CONCLUSIONS

The following conclusions can be drawn:

1/ While the supporting frame (two 4-inch aluminum angles bolted to the housings of the sensor) for the RIMS sensor was apparently inadequate for the field tests, the RIMS sensor itself appeared to have withstood the relatively harsh field conditions.

2/ Despite the relatively crude test configuration, the RIMS allowed a large number of profile measurements to be obtained efficiently and effectively.

3/ The RIMS measurements compared very well against their manual counterparts: for the majority of measurements, differences were in the order of 1/32 inch. In addition, the recorded profiles provided very valuable information about the general physical conditions and, in particular, the wear trends of the rails, and allowed the maintenance engineer to conduct reviews efficiently when necessary.

In summary, the field testing program achieved considerable success in being able to demonstrate the tremendous potential of using a vision-based system to monitor rail wear.

## 9/ RECOMMENDATIONS

It is believed that a vision-based rail wear monitoring system will be a sound and viable alternative to existing manual procedures by greatly enhancing effectiveness and efficiency, and by making available, in a very convenient and systematic manner, valuable information on the condition of the rail to property management. It is also believed that the information and experience that has been gathered to date have provided a firm basis for proceeding with the development of a much improved vision system that will employ more intelligent and accurate image processing techniques than what is being used by the RIMS. As a prelude to this venture, it is recommended that the following tasks be performed:

- performance of a meaningful cost-benefit analysis that is based on the existing work program and on an improved and practicable one that will allow greater realization of the potential benefits of using automated machine vision;

- development of requirements and specifications for an improved vision-based rail wear monitoring system that will employ state-of-the-art pattern recognition and data processing techniques; and

- development of appropriate operational procedures for the above-mentioned system with due consideration given to existing maintenance procedures.

**Table 1: Comparison of Vision-based and Manual Measurements (in 1/16 in.) for Test Set 2**

| Test Locations (Chainage) | RIMS | | Manual (TTC) | | Vision-Manual | |
|---|---|---|---|---|---|---|
| | Head Wear | Gauge Wear | Head Wear | Gauge Wear | Head Wear | Gauge Wear |
| LR-A1 (526+00) | 1.05 | 0.00 | 1.57 | 0.00 | -0.52 | 0.00 |
| LR-A2 (525+50) | 2.82 | -0.42 | 2.84 | 0.00 | -0.02 | n/a |
| LR-B1 (525+00) | 4.80 | -0.64 | 3.74 | 0.00 | 1.06 | n/a |
| LR-B2 (524+50) | 5.64 | -0.64 | 4.34 | 0.00 | 1.30 | n/a |
| LR-B3 (524+00) | 5.85 | -0.64 | 3.74 | 0.00 | 2.11 | n/a |
| LR-B4 (523+50) | 6.05 | -0.64 | 3.74 | 0.00 | 2.31 | n/a |
| LR-C1 (523+00) | 4.49 | -0.42 | 3.74 | 0.00 | 0.75 | n/a |
| LR-C2 (522+50) | 1.98 | -0.42 | 1.57 | 0.00 | 0.41 | n/a |
| LR-C4 (522+00) | 2.19 | 0.64 | 2.21 | 0.00 | -0.02 | 0.64 |
| LR-C5 (521+50) | 1.25 | -0.84 | 1.57 | 0.00 | -0.32 | n/a |
| LR-C6 (521+00) | 1.78 | 0.00 | 1.57 | 0.00 | 0.21 | 0.00 |
| LR-C7 (520+50) | 1.56 | 0.84 | 1.57 | 0.00 | -0.01 | 0.84 |
| HR-A1 (520+50) | 1.67 | -0.21 | 1.57 | 0.00 | 0.10 | n/a |
| HR-B1 (521+00) | 2.40 | -0.21 | 1.89 | 0.00 | 0.51 | n/a |
| HR-B2 (521+50) | 2.82 | -0.21 | 1.57 | 0.32 | 1.25 | n/a |
| HR-B3 (522+00) | 2.09 | -0.42 | 1.89 | 0.00 | 0.20 | n/a |
| HR-C1 (522+50) | 0.84 | 1.48 | 0.32 | 0.63 | 0.52 | 0.85 |
| HR-C2 (523+00) | 1.88 | 5.29 | 1.26 | 4.94 | 0.62 | 0.35 |
| HR-C3 (523+50) | 2.09 | 4.45 | 1.57 | 4.64 | 0.52 | -0.19 |
| HR-D1 (524+00) | 1.56 | 5.29 | 1.26 | 5.54 | 0.30 | -0.25 |
| HR-D2 (524+50) | 1.78 | 4.66 | 1.57 | 6.74 | 0.21 | -2.08 |
| HR-D3 (525+00) | 1.46 | 5.71 | 1.26 | 6.44 | 0.20 | -0.73 |
| HR-D4 (525+50) | 0.31 | 2.75 | 0.63 | 1.57 | -0.32 | 1.18 |
| HR-D5 (526+00) | 1.56 | -0.64 | 0.32[1] | 0.00 | 1.24 | n/a |

[1] An examination of the profile plot for this location seems to show that this value has been significantly under-estimated.

**Table 2: Comparison of Rail Wear as "Percent Railhead Area Loss" for Test Set 2**

| Test Locations (Chainage) | Rail Wear as Percent Railhead Area Loss | | Difference |
|---|---|---|---|
| | RIMS | Manual | |
| LR-A1 (526+00) | 2.98 | 5.03 | -2.05 |
| LR-A2 (525+50) | 10.17 | 10.26 | -0.09 |
| LR-B1 (525+00) | 18.88 | 14.16 | 4.72 |
| LR-B2 (524+50) | 22.67 | 16.82 | 5.85 |
| LR-B3 (524+00) | 23.62 | 14.16 | 9.46 |
| LR-B4 (523+50) | 24.53 | 14.16 | 10.37 |
| LR-C1 (523+00) | 17.49 | 14.16 | 3.33 |
| LR-C2 (522+50) | 6.64 | 5.03 | 1.61 |
| LR-C4 (522+00) | 11.18 | 7.60 | 3.58 |
| LR-C5 (521+50) | 3.77 | 5.03 | -1.26 |
| LR-C6 (521+00) | 5.85 | 5.03 | 0.82 |
| LR-C7 (520+50) | 8.72 | 5.03 | 3.69 |
| HR-A1 (520+50) | 5.42 | 5.03 | 0.39 |
| HR-B1 (521+00) | 8.40 | 6.29 | 2.11 |
| HR-B2 (521+50) | 13.15 | 8.07 | 5.08 |
| HR-B3 (522+00) | 7.10 | 6.29 | 0.81 |
| HR-C1 (522+50) | 6.65 | 3.75 | 2.90 |
| HR-C2 (523+00) | 17.02 | 13.78 | 3.24 |
| HR-C3 (523+50) | 16.52 | 14.60 | 1.92 |
| HR-D1 (524+00) | 15.66 | 14.81 | 0.85 |
| HR-D2 (524+50) | 15.53 | 18.22 | -2.69 |
| HR-D3 (525+00) | 15.95 | 16.37 | -0.42 |
| HR-D4 (525+50) | 6.68 | 6.06 | 0.62 |
| HR-D5 (526+00) | 4.99 | 0.94[1] | 4.05 |

[1]This value appears to have been significantly under-estimated (see footnote for Table 1).

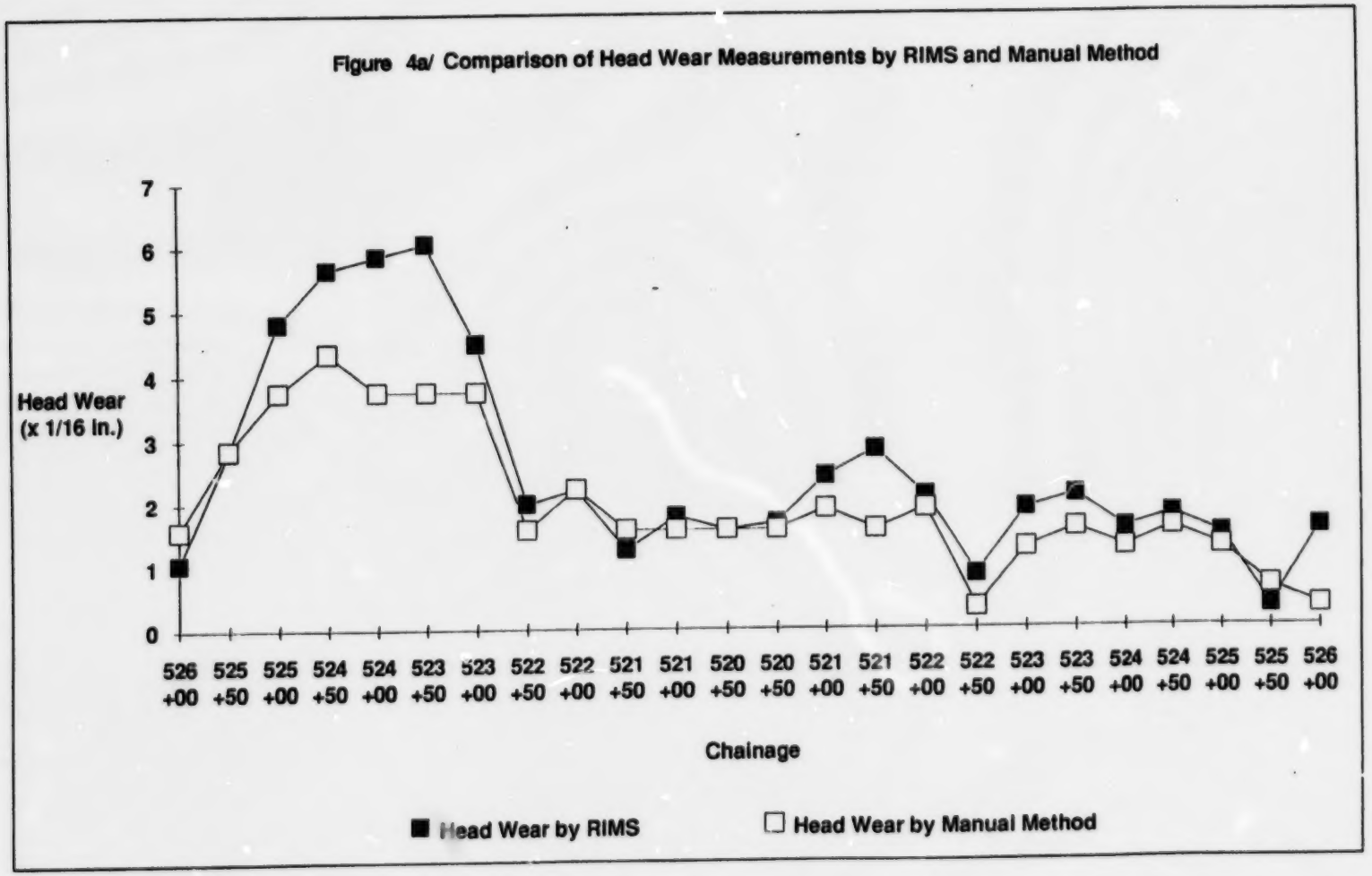
Figure 4a/ Comparison of Head Wear Measurements by RIMS and Manual Method
Head Wear (x 1/16 in.)
0
1
2
3
4
5
6
7
526 +00
525 +50
525 +00
524 +50
524 +00
523 +50
523 +00
522 +50
522 +00
521 +50
521 +00
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Chainage
Head Wear by RIMS
Head Wear by Manual Method

Figure 4b/ Differences in Head Wear Measurements between RIMS and Manual Method

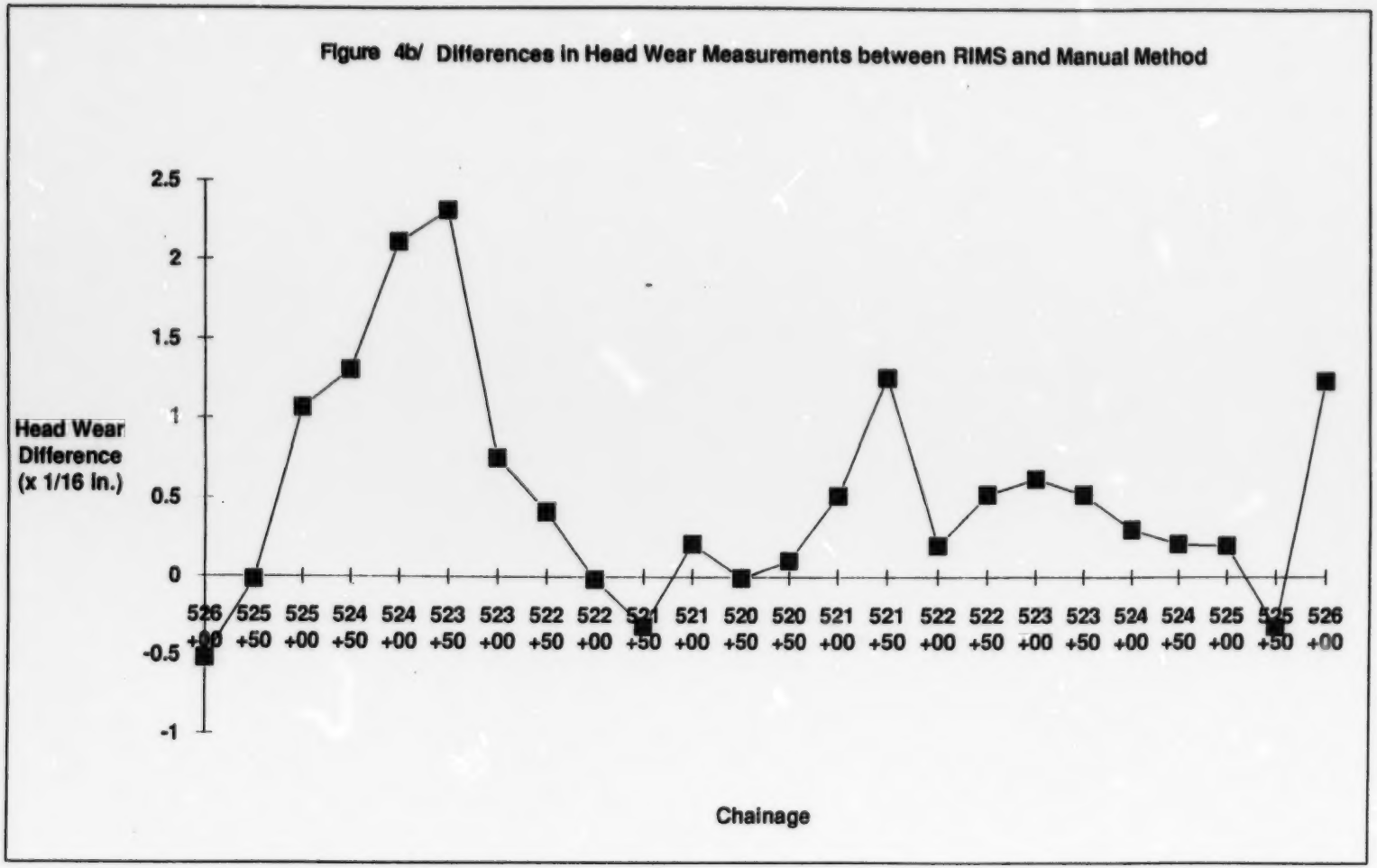


Figure 5a/ Comparison of Gauge Wear Measurements by RIMS and Manual Method

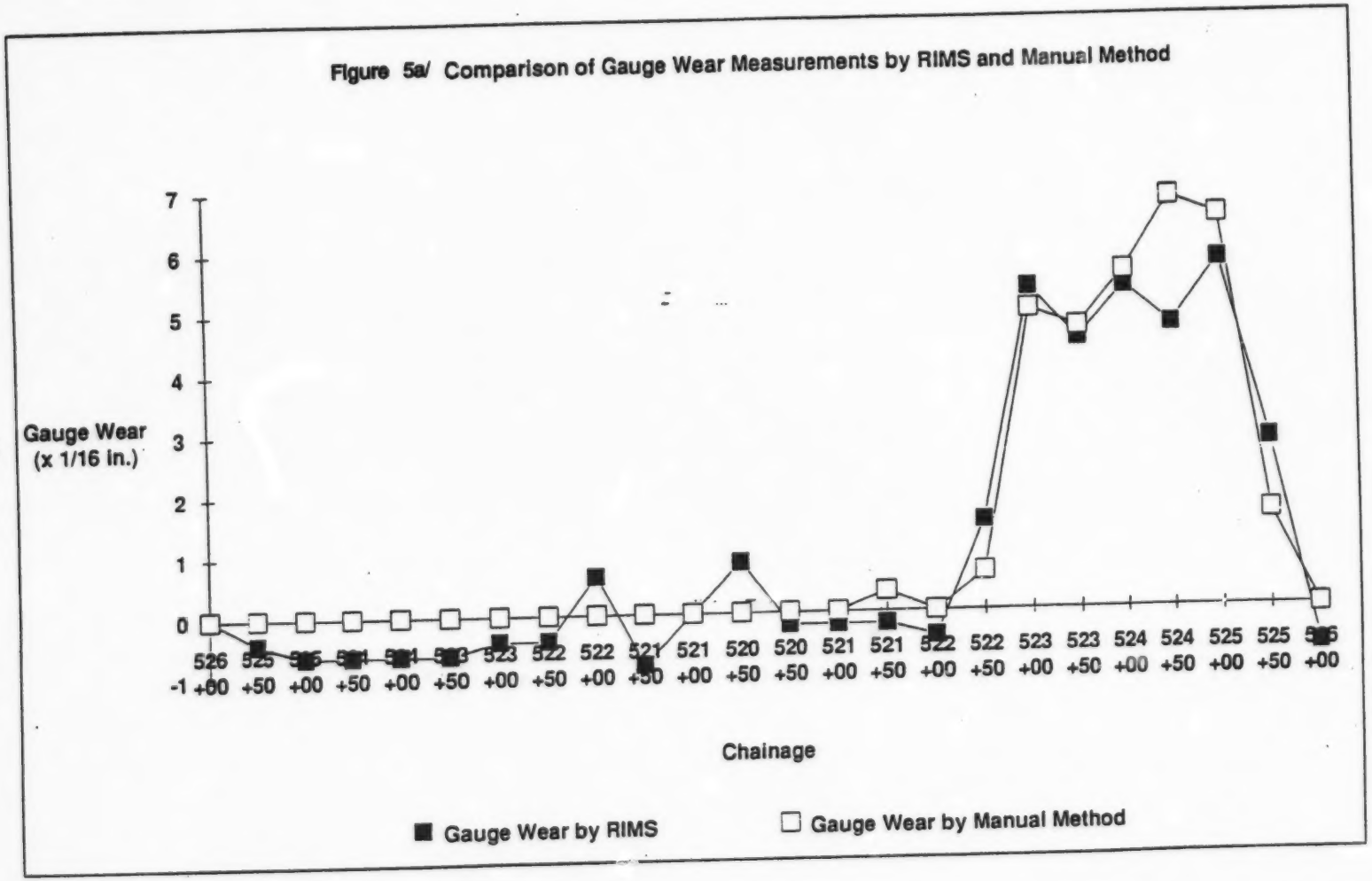
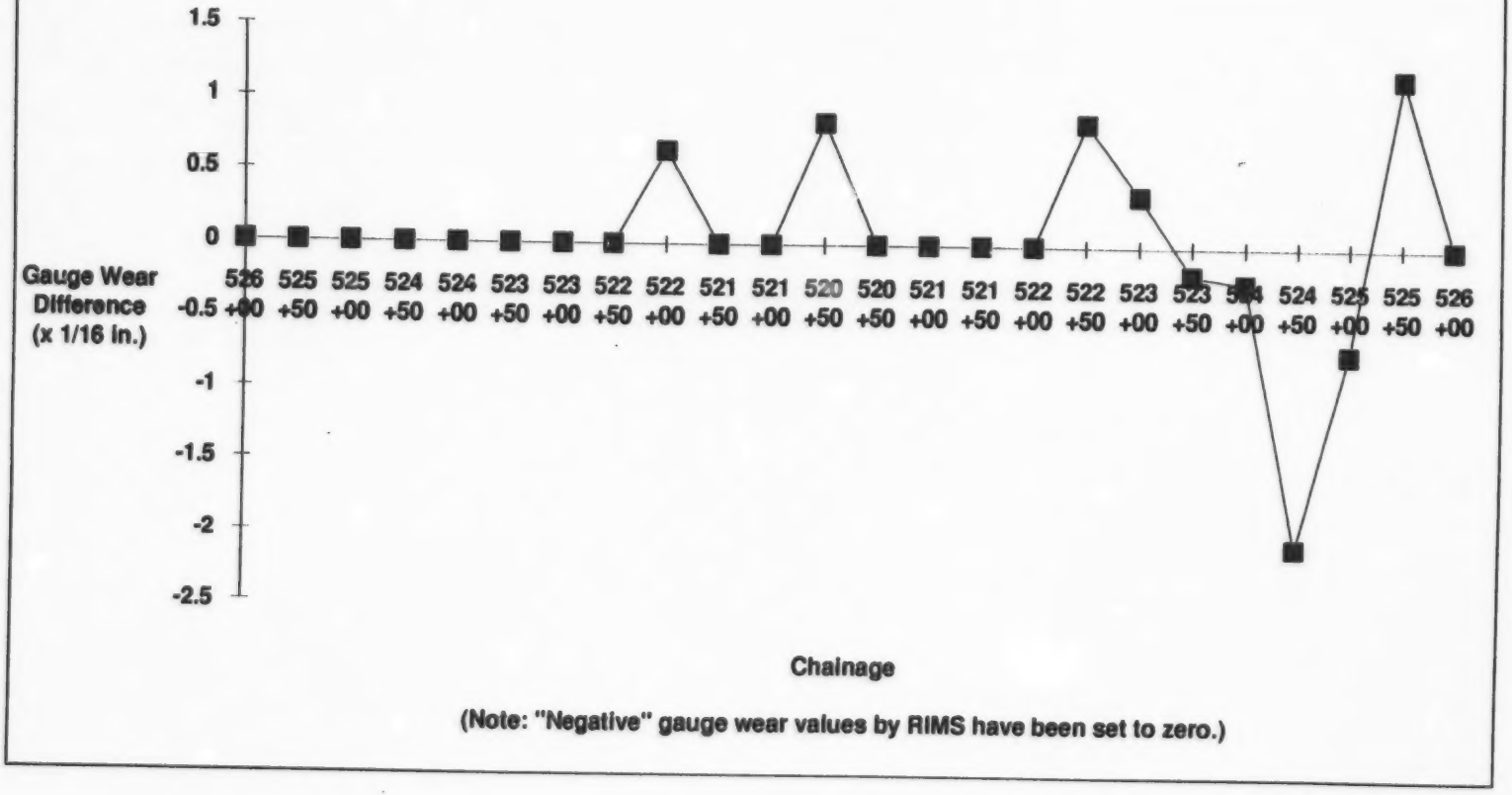


Figure 5b/ Differences in Gauge Wear Measurements between RIMS and Manual Method




(Note: "Negative" gauge wear values by RIMS have been set to zero.)

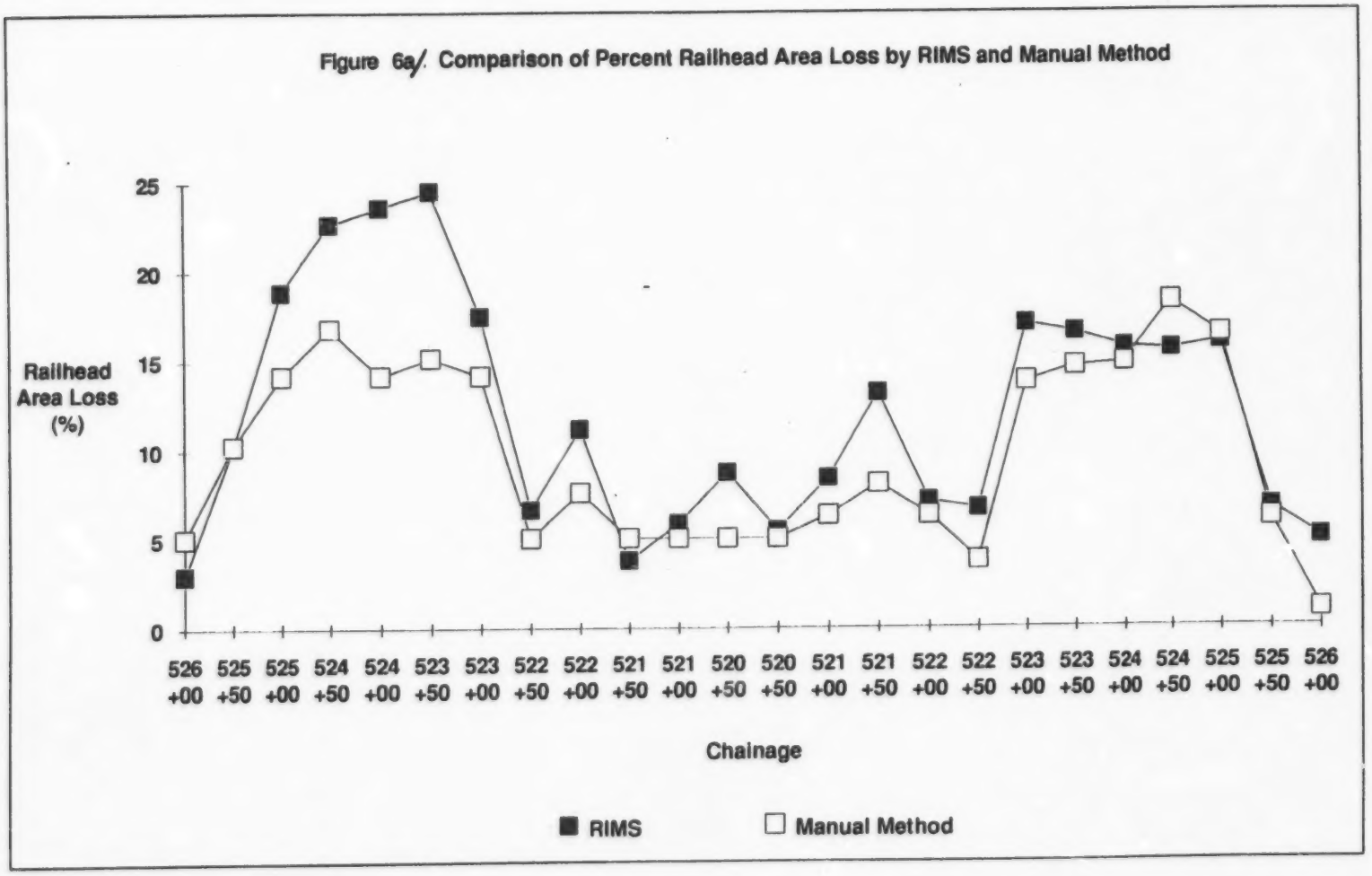
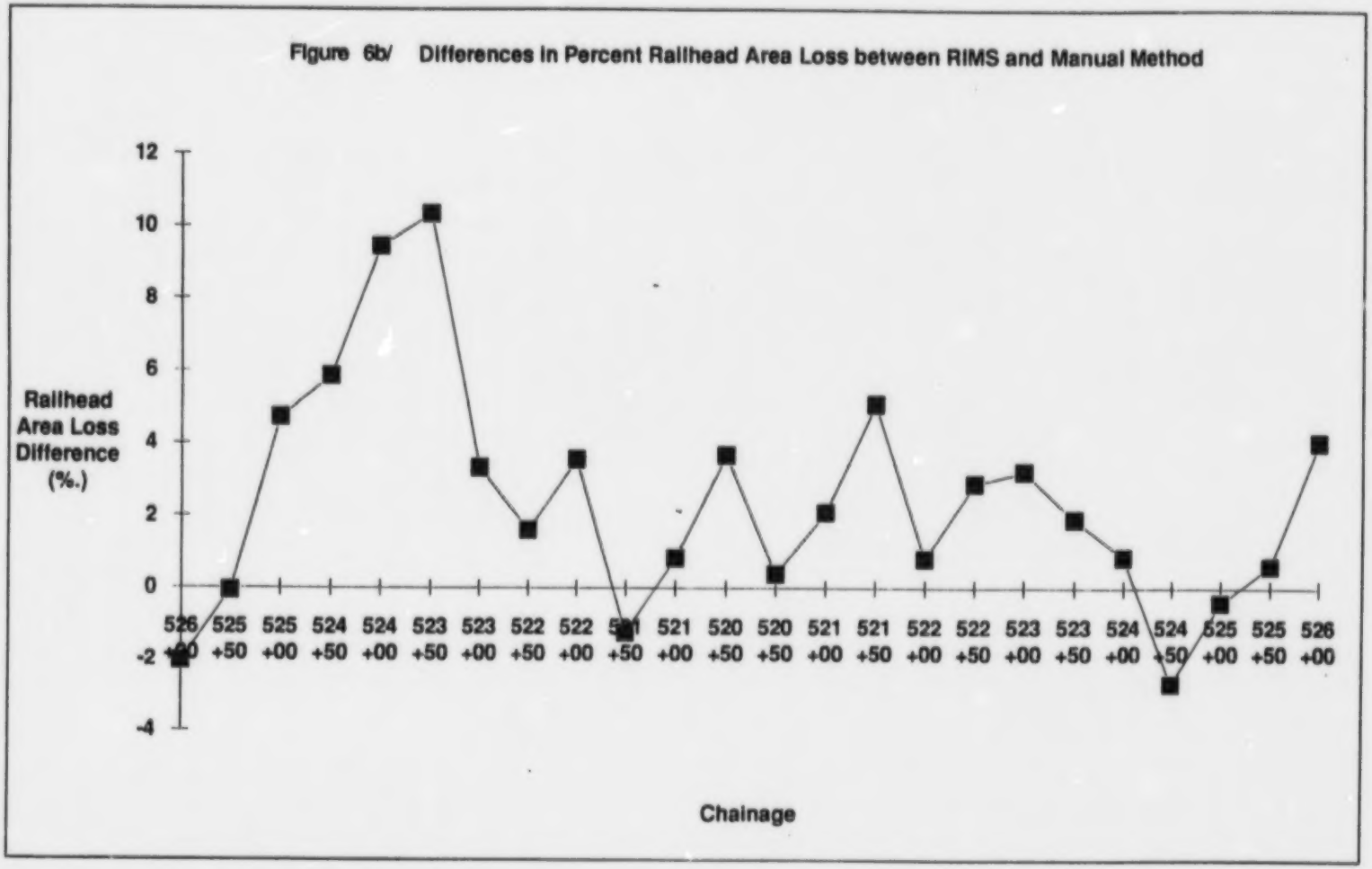


Figure 6a/. Comparison of Percent Railhead Area Loss by RIMS and Manual Method
Railhead Area Loss (%)
25
20
15
10
5
0
526 +00
525 +50
525 +00
524 +50
524 +00
523 +50
523 +00
522 +50
522 +00
521 +50
521 +00
520 +50
520 +00
521 +00
521 +50
522 +00
522 +50
523 +00
523 +50
524 +00
524 +50
525 +00
525 +50
526 +00
Chainage
RIMS
Manual Method

Figure 6b/ Differences in Percent Railhead Area Loss between RIMS and Manual Method



## REFERENCES

1/ Leung, D.K.W., "Application of Machine Vision to Wheel/Rail Maintenance," The 9th International Wheelset Congress, Montreal, Canada, September 1988.

2/ Leung, D.K.W., "Laboratory Evaluation of a Prototype Vision System for Automated Rail Profile Measurement," Report #RT-91-01, Ministry of Transportation, Ontario, Canada, September 1990.

## APPENDIX I

Printer Plots and Wear Measurements of Typical Rail Profiles

for Test Set 1

(Note: plots are not to exact scale.)

**NOMENCLATURE**

| | |
|---|---|
| h: | Height of railhead in pixels. |
| wf: | Half-width of railhead w.r.t. field side in pixels. |
| wg: | Half-width of railhead w.r.t. gauge side in pixels. |
| cantdel: | Factor to account for rail cant |

SHER401.DAT

NOTE: Field refers to LHS of image, Gauge to RHS

Head Height = 27.33 mm
Width Field = 33.93 mm
Width Gauge = 33.93 mm
Lip Value = 0.00 mm
Head Wear = 3.31 mm
Width Field Wear = 0.00 mm
Width Gauge Wear = 0.00 mm
h = 165 pixels
wf = 181 pixels
wg = 181 pixels
cantdel =4

SHERW06.DAT

NOTE: Field refers to LHS of image, Gauge to RHS

Head Height = 27.83 mm
Width Field = 33.93 mm
Width Gauge = 34.27 mm
Lip Value = 0.00 mm
Head Wear = 2.82 mm
Width Field Wear = 0.00 mm
Width Gauge Wear = -0.34 mm
h = 168 pixels
wf = 181 pixels
wg = 182 pixels
cantdel =4

$HERM07.DAT

NOTE: Field refers to LHS of image, Gauge to RHS

Head Height = 26.34 mm
Width Field = 34.61 mm
Width Gauge = 33.60 mm
Lip Value = 0.00 mm
Head Wear = 4.31 mm
Width Field Wear = -0.67 mm
Width Gauge Wear = 0.34 mm
h = 159 pixels
wf = 103 pixels
wg = 100 pixels
cantdel =4

$HERWB12.DAT

NOTE: Field refers to LHS of image, Gauge to RHS

---

Head Height = 28.82 mm
Width Field = 34.27 mm
Width Gauge = 29.98 mm
Lip Value = 0.00 mm
Head Wear = 1.82 mm
Width Field Wear = -0.34 mm
Width Gauge Wear = 4.03 mm
h = 174 pixels
wf = 182 pixels
wg = 89 pixels
cantdel =4

1378.001

NOTE: Field refers to LHS of image, Gauge to RHS

---

Head Height = 26.01 mm
Width Field = 34.27 mm
Width Gauge = 34.61 mm
Lip Value = 0.00 mm
Head Wear = 4.64 mm
Width Field Wear = -0.34 mm
Width Gauge Wear = -0.67 mm
h = 157 pixels
wf = 102 pixels
wg = 103 pixels
cantdel =4

9547B.DAT

NOTE: Field refers to LHS of image, Gauge to RHS

| | |
|---|---|
| Head Height | = 27.17 mm |
| Width Field | = 33.93 mm |
| Width Gauge | = 27.55 mm |
| Lip Value | = 0.00 mm |
| Head Wear | = 3.48 mm |
| Width Field Wear | = 0.00 mm |
| Width Gauge Wear | = 6.38 mm |

h = 164 pixels
wf = 181 pixels
wg = 82 pixels
cantdel =4

## APPENDIX II

Printer Plots and Wear Measurements of Typical Rail Profiles

for Test Set 2

(Note: plots are not to exact scale.)

**NOMENCLATURE**

h: Height of railhead in pixels.

wf: Half-width of railhead w.r.t. field side in pixels.

wg: Half-width of railhead w.r.t. gauge side in pixels.

cantdel: Factor to account for rail cant

LRA1.DAT (526+oc)

NOTE: Field refers to LHS of image, Gauge to RHS

---

Head Height = 28.99 mm
Width Field = 33.93 mm
Width Gauge = 33.93 mm
Lip Value = 0.00 mm
Head Wear = 1.66 mm
Width Field Wear = 0.00 mm
Width Gauge Wear = 0.00 mm
h = 175 pixels
uf = 101 pixels
ug = 101 pixels
cantdel =4

LRA2.DAT (525+52)

NOTE: Field refers to LHS of image, Gauge to RHS

---

Head Height = 26.17 mm
Width Field = 33.93 mm
Width Gauge = 34.61 mm
Lip Value = 0.00 mm
Head Wear = 4.47 mm
Width Field Wear = 0.00 mm
Width Gauge Wear = -0.67 mm
h = 158 pixels
uf = 101 pixels
ug = 103 pixels
cantdel =4

LRB1.DAT (525+00)

NOTE: Field refers to LHS of image, Gauge to RHS

Head Height = 23.83 mm
Width Field = 33.93 mm
Width Gauge = 34.94 mm
Lip Value = 0.00 mm
Head Wear = 7.62 mm
Width Field Wear = 0.00 mm
Width Gauge Wear = -1.01 mm
h = 139 pixels
uf = 101 pixels
ug = 104 pixels
cantdel =4

LNCS.DAT (52+50)

NOTE: Field refers to LHS of image, Gauge to RHS

Head Height = 28.66 mm
Width Field = 34.27 mm
Width Gauge = 35.28 mm
Lip Value = 0.00 mm
Head Wear = 1.99 mm
Width Field Wear = -0.34 mm
Width Gauge Wear = -1.34 mm
h = 173 pixels
wf = 182 pixels
wg = 185 pixels
cantdel =4

HRC1.DAT (522+52)

NOTE: Field refers to LHS of image, Gauge to RHS

| | |
|---|---|
| Head Height | = 29.32 mm |
| Width Field | = 33.93 mm |
| Width Gauge | = 31.58 mm |
| Lip Value | = 0.00 mm |
| Head Wear | = 1.33 mm |
| Width Field Wear | = 0.00 mm |
| Width Gauge Wear | = 2.35 mm |

h = 177 pixels
wf = 181 pixels
wg = 94 pixels
cantdel =4

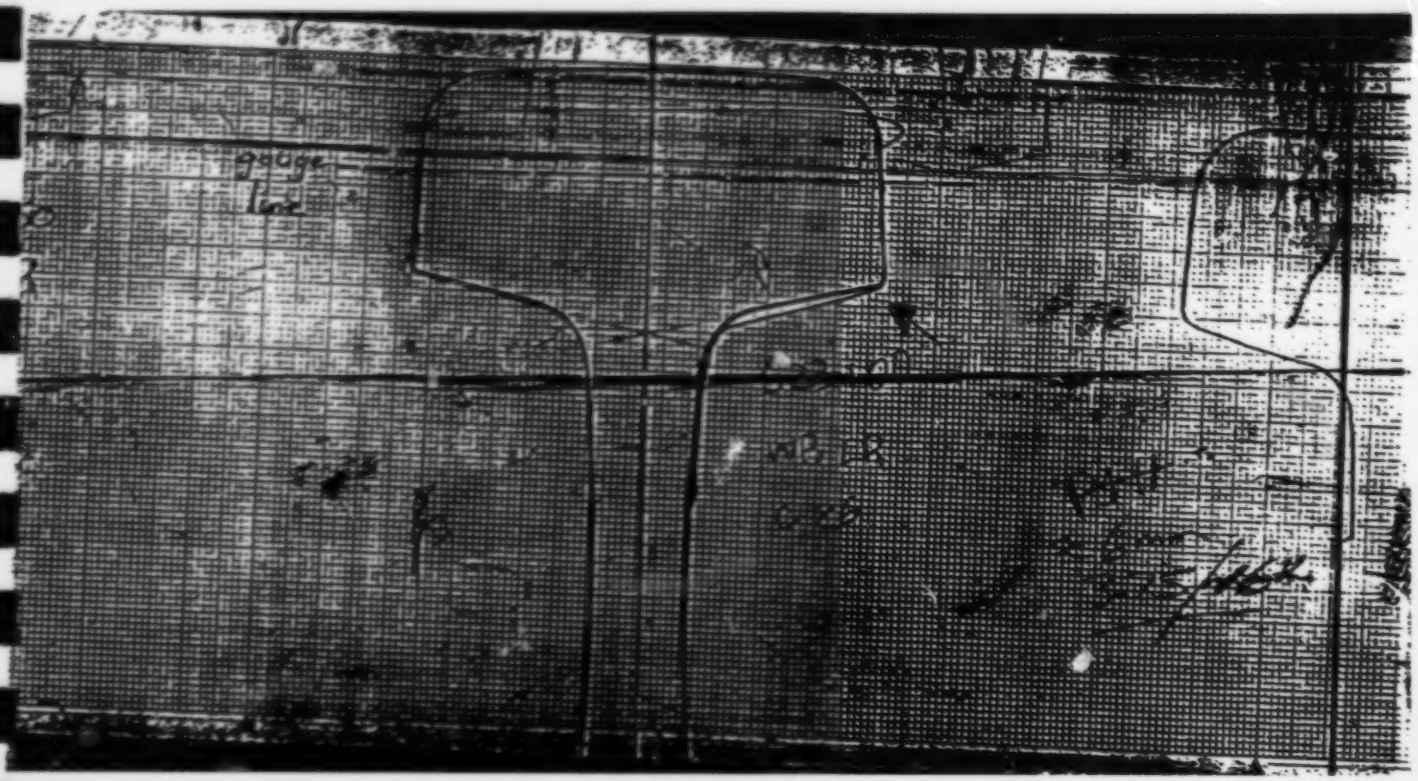
HRD1.DAT (12404)

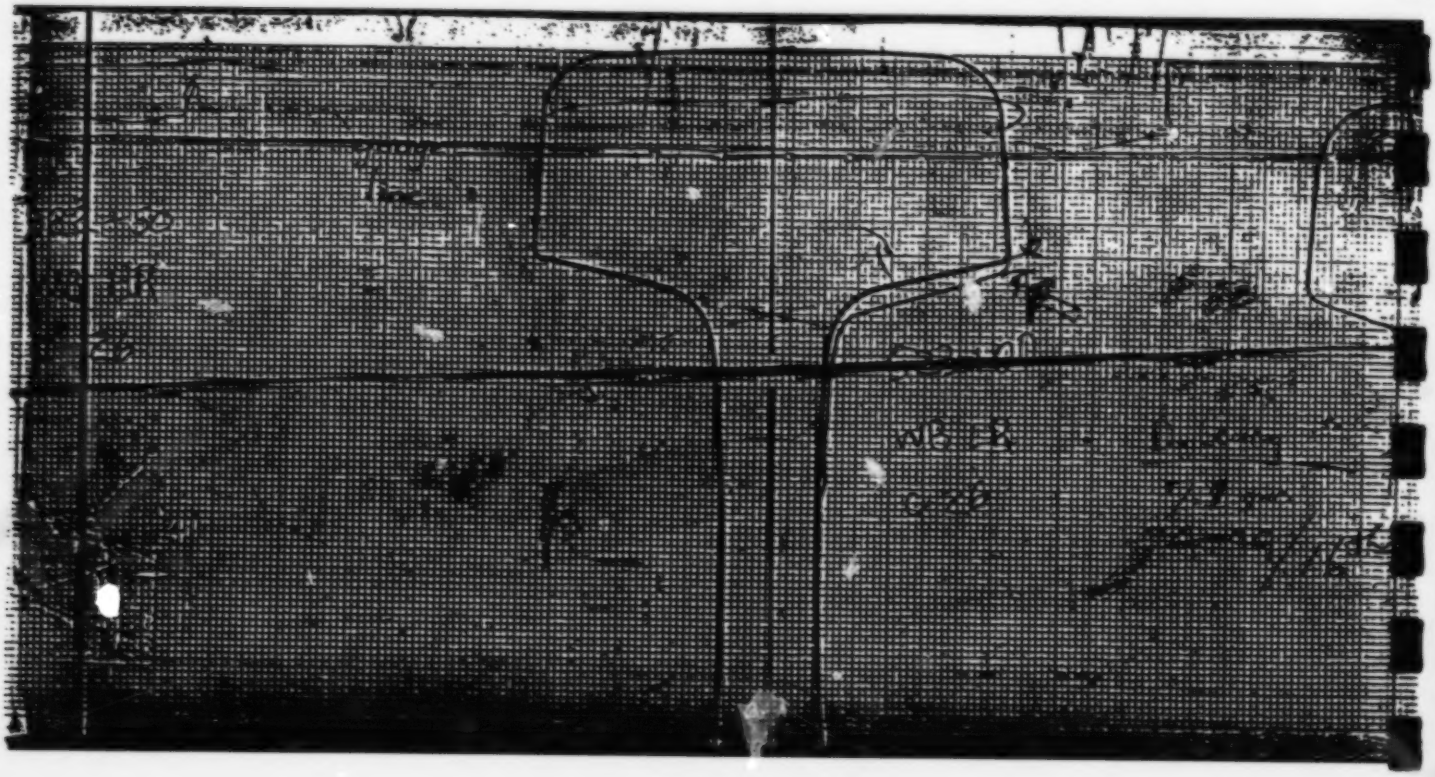
NOTE: Field refers to LHS of image, Gauge to RHS

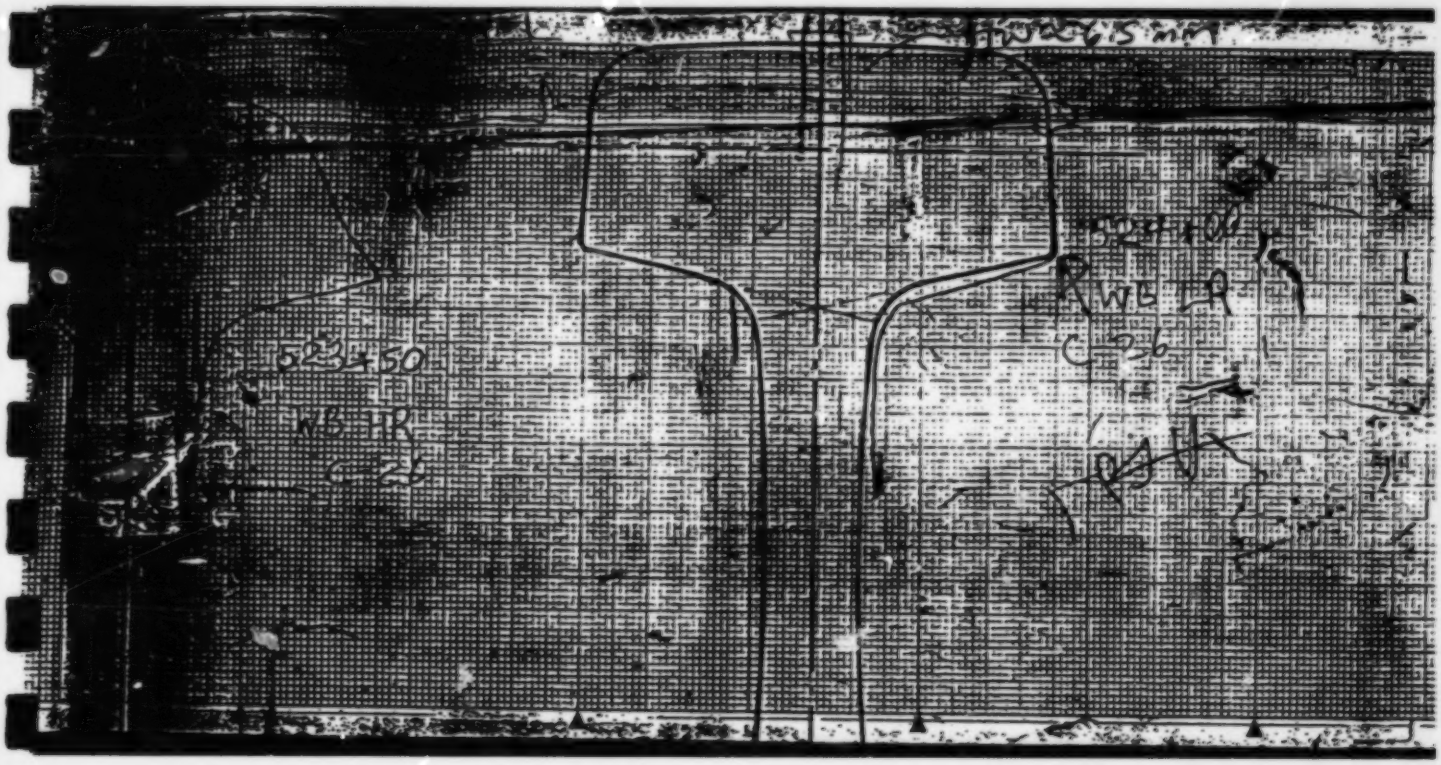
| | |
|---|---|
| Head Height | = 28.16 mm |
| Width Field | = 34.27 mm |
| Width Gauge | = 25.53 mm |
| Lip Value | = 0.00 mm |
| Head Wear | = 2.48 mm |
| Width Field Wear | = -0.34 mm |
| Width Gauge Wear | = 8.48 mm |
| h | = 170 pixels |
| wf | = 102 pixels |
| wg | = 76 pixels |
| cantdel | =4 |

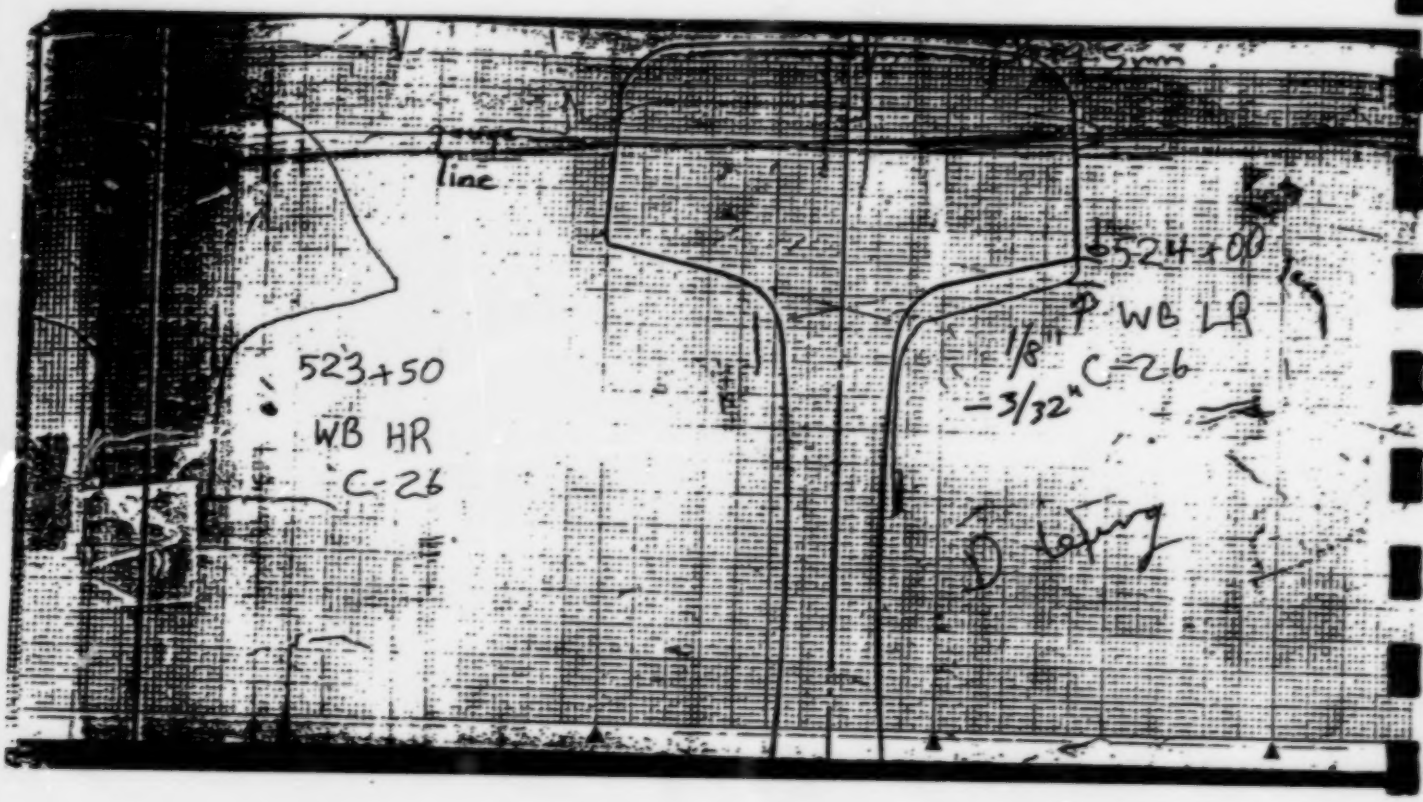
## APPENDIX III

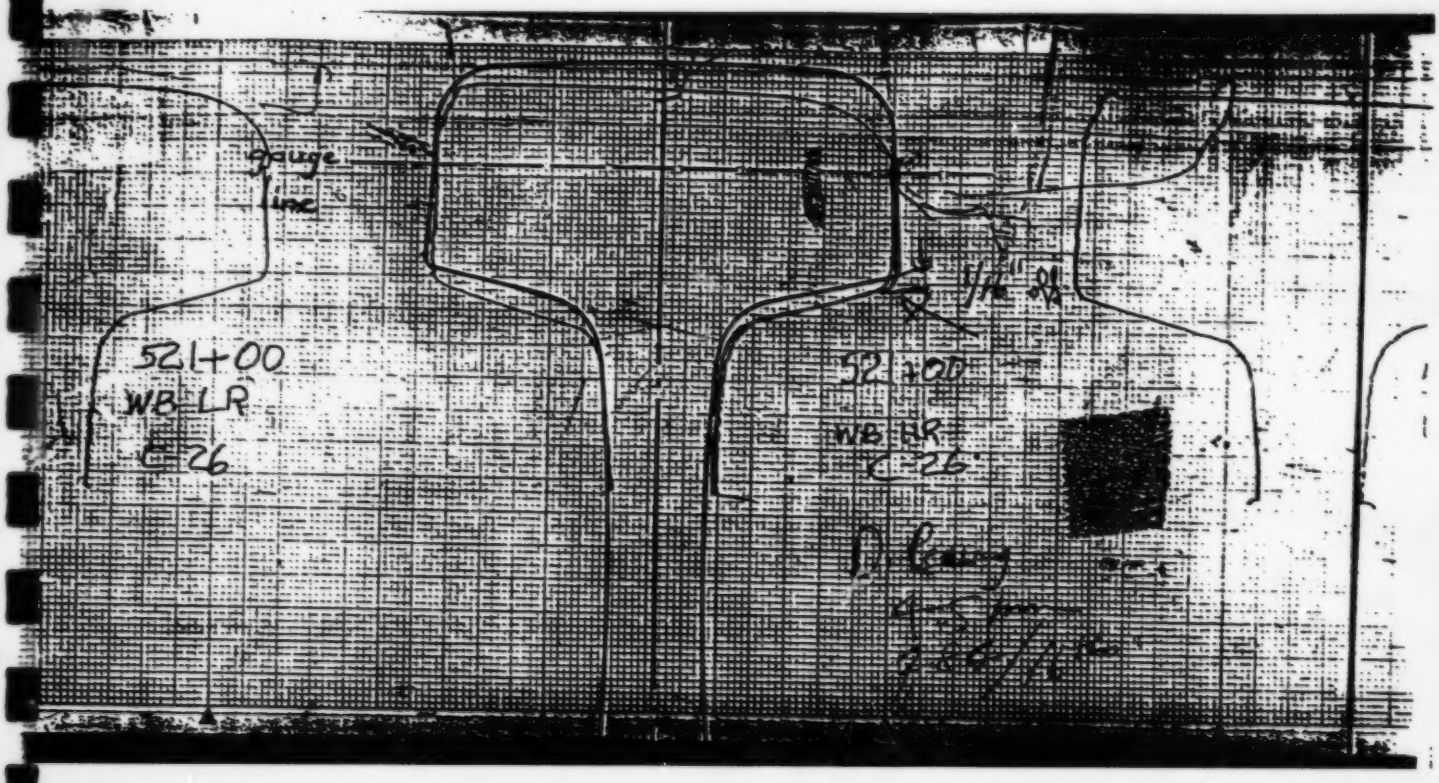
Selected Rail Profiles as Traced by TTC

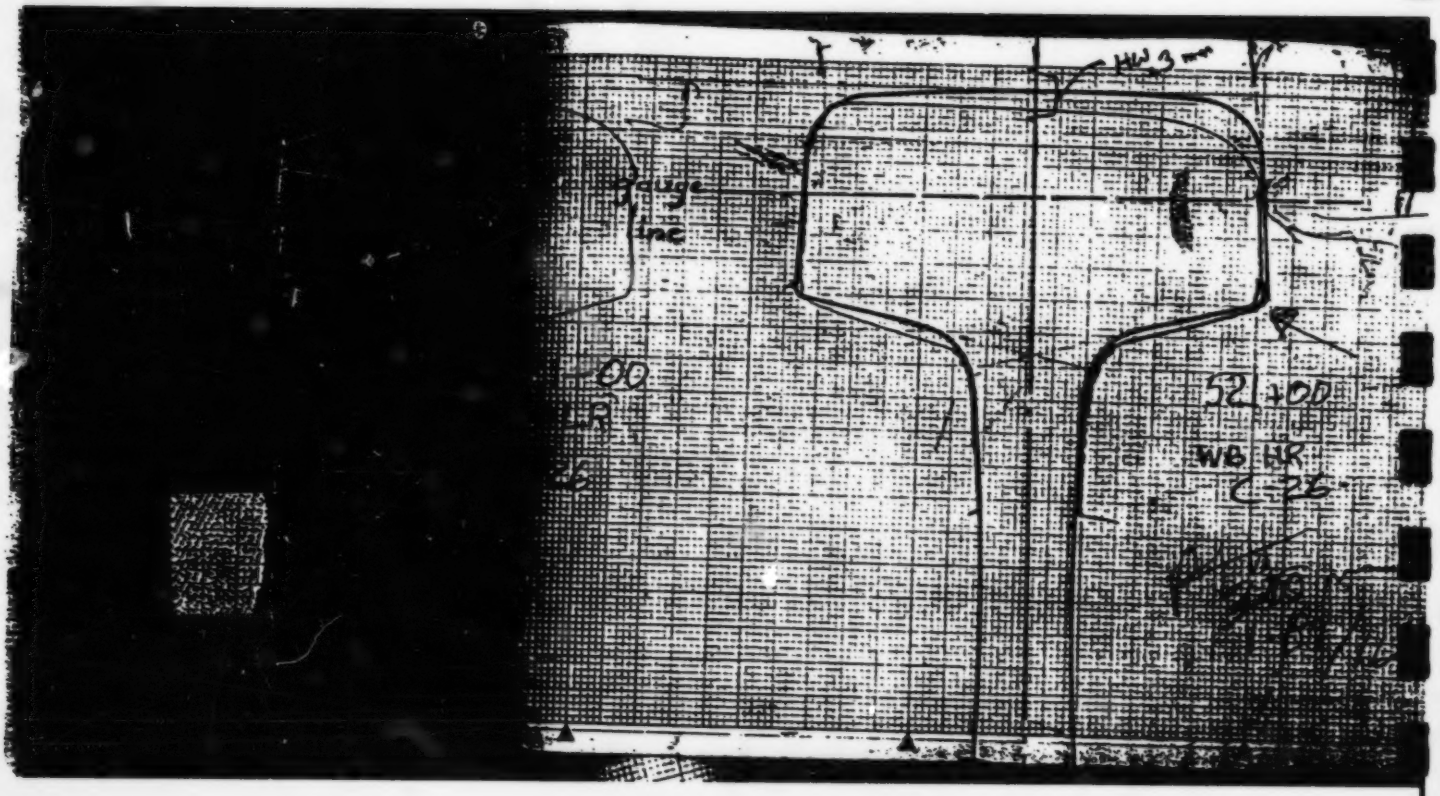

gauge
line

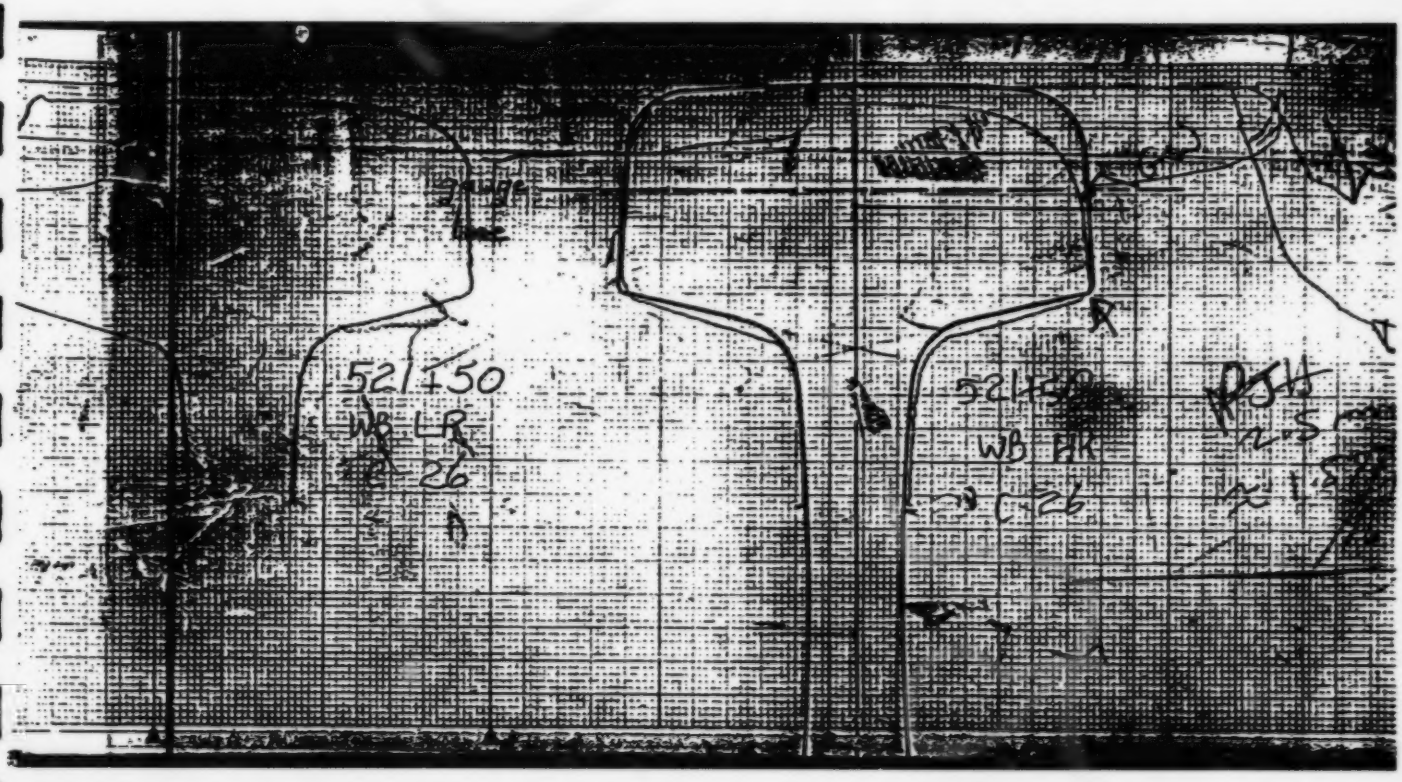


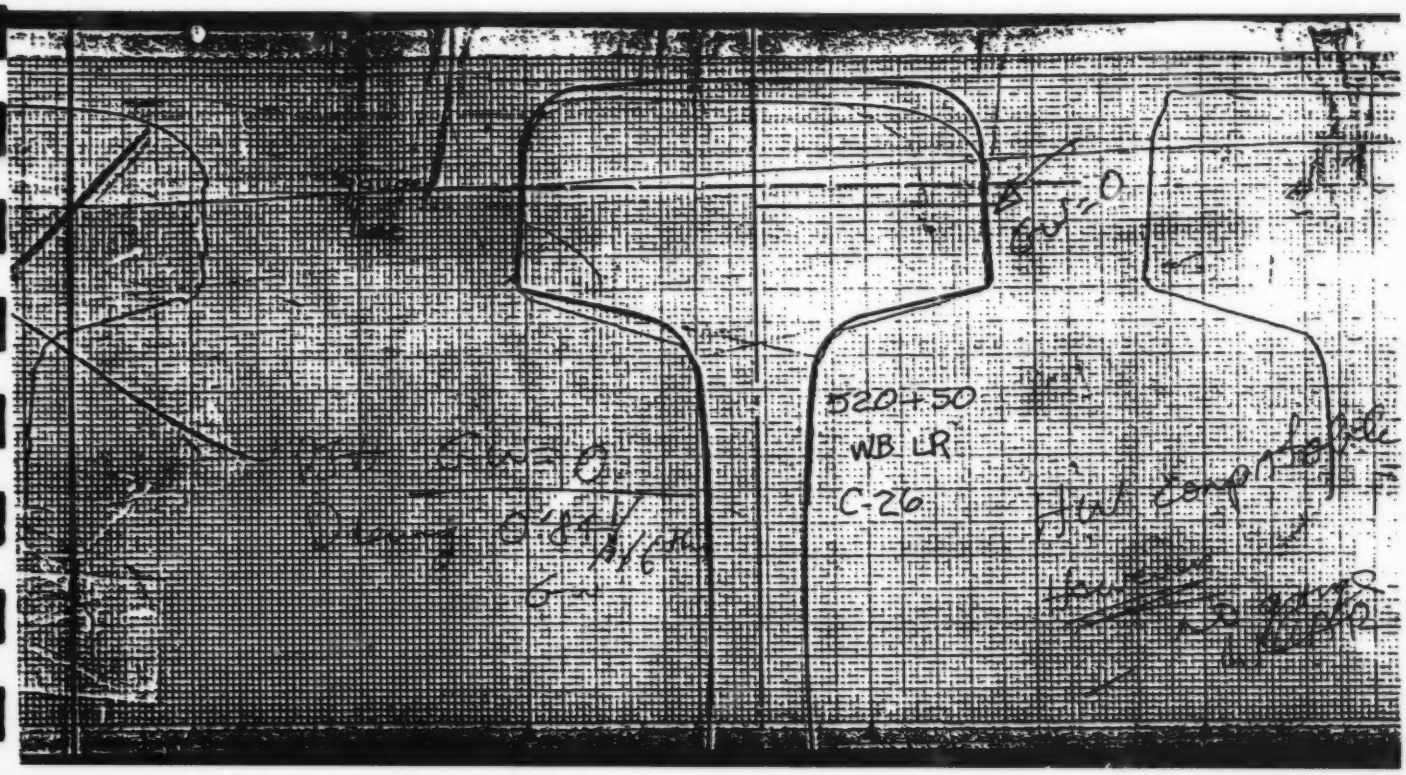

WB HR
C 26

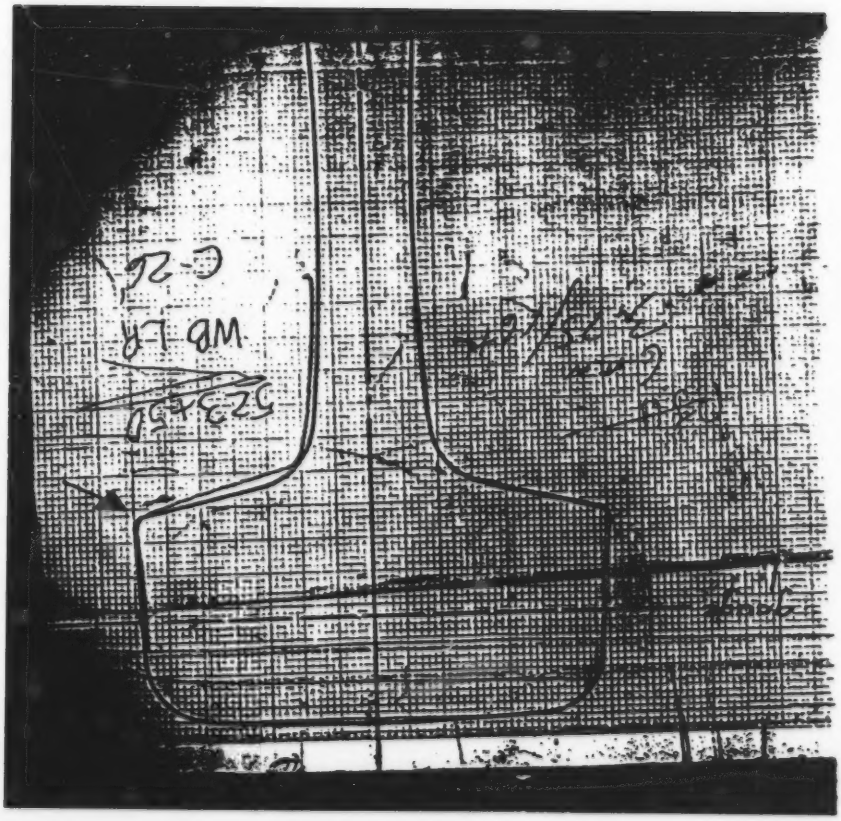

line
523+50
WB HR
C-26
524+00
WB LR
1/8"
-3/32"
C-26

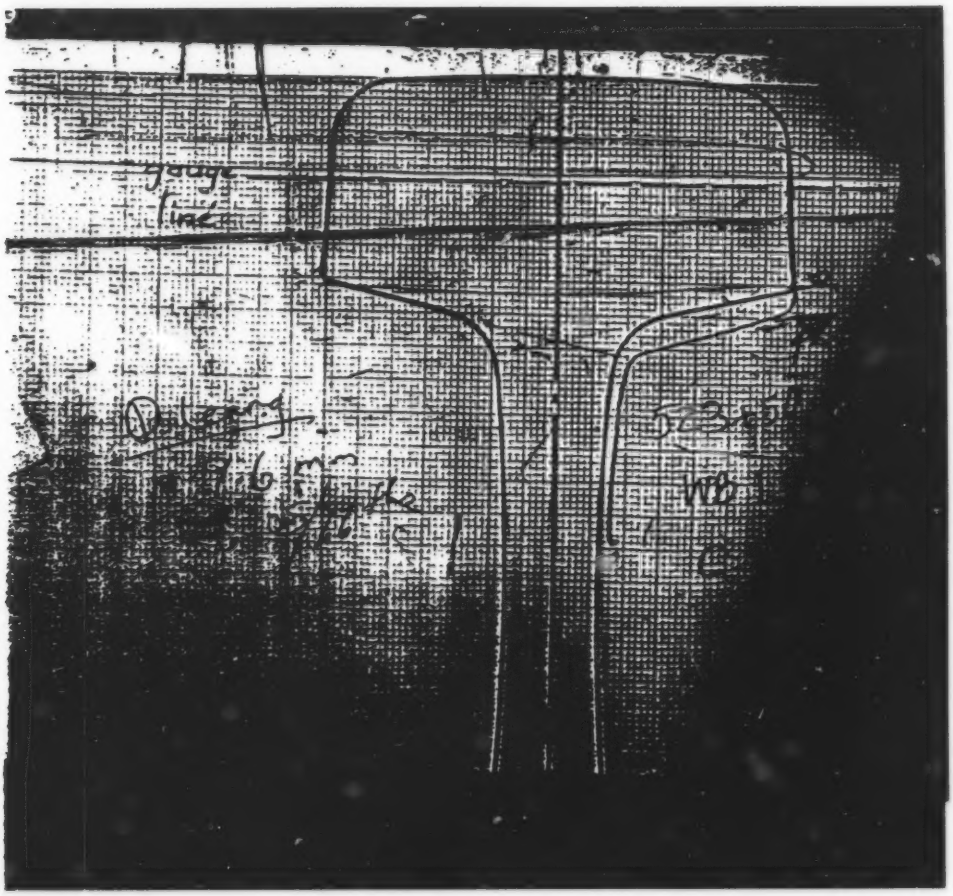

gauge
line
521+00
WB LR
℄ 26
52 +00
WB LR
℄ 26

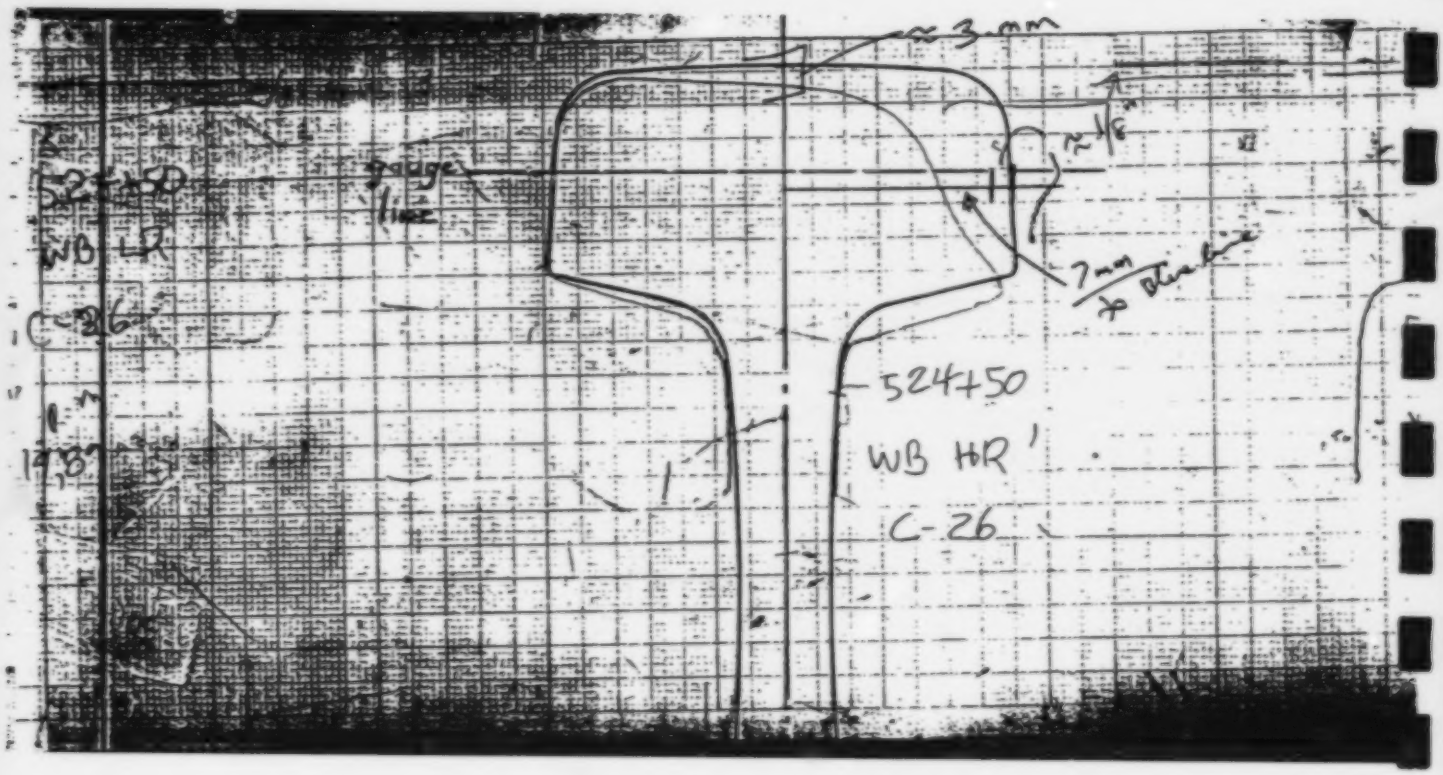

HW 3
gauge line
00
LR
52 +OD
WB HR
C 25

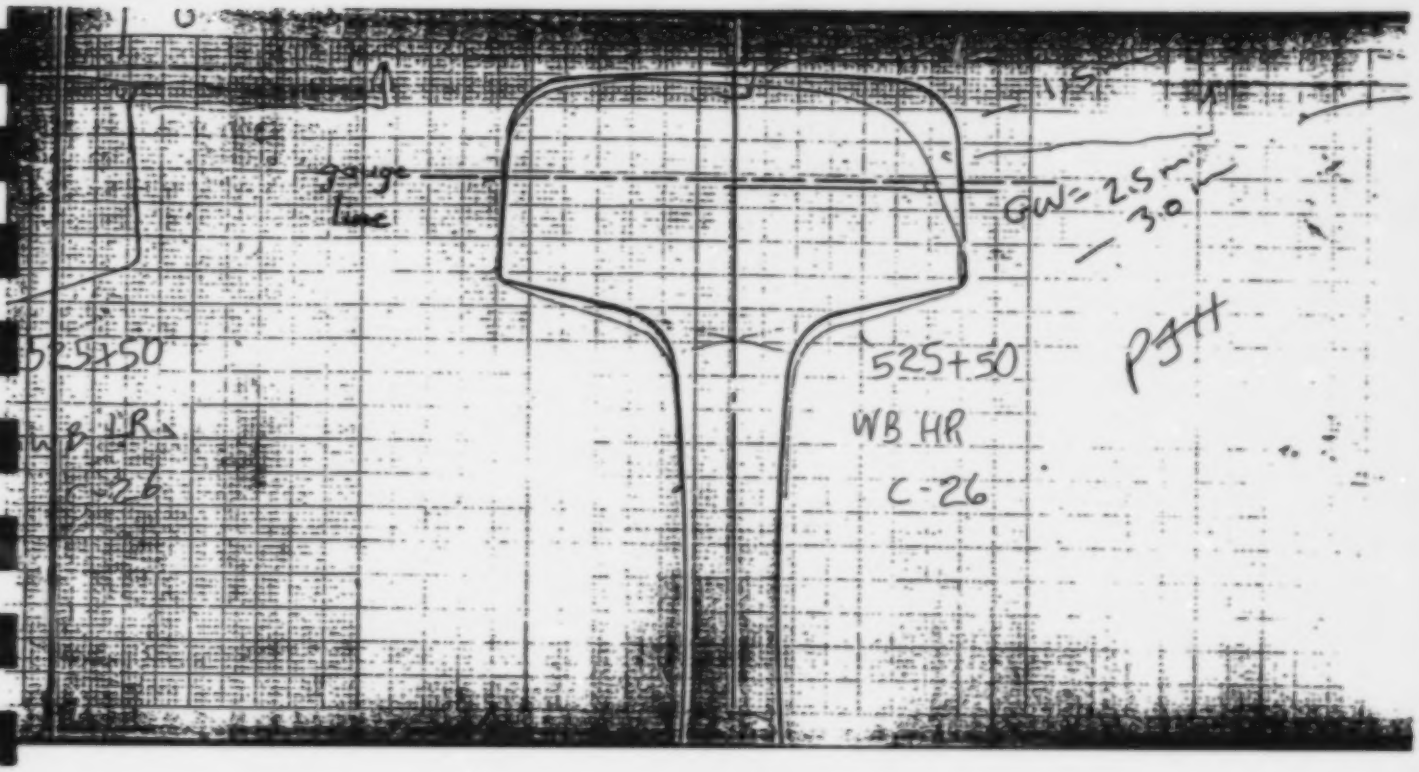

52/50
WB R
C 26
52/50
WB RK
C 26

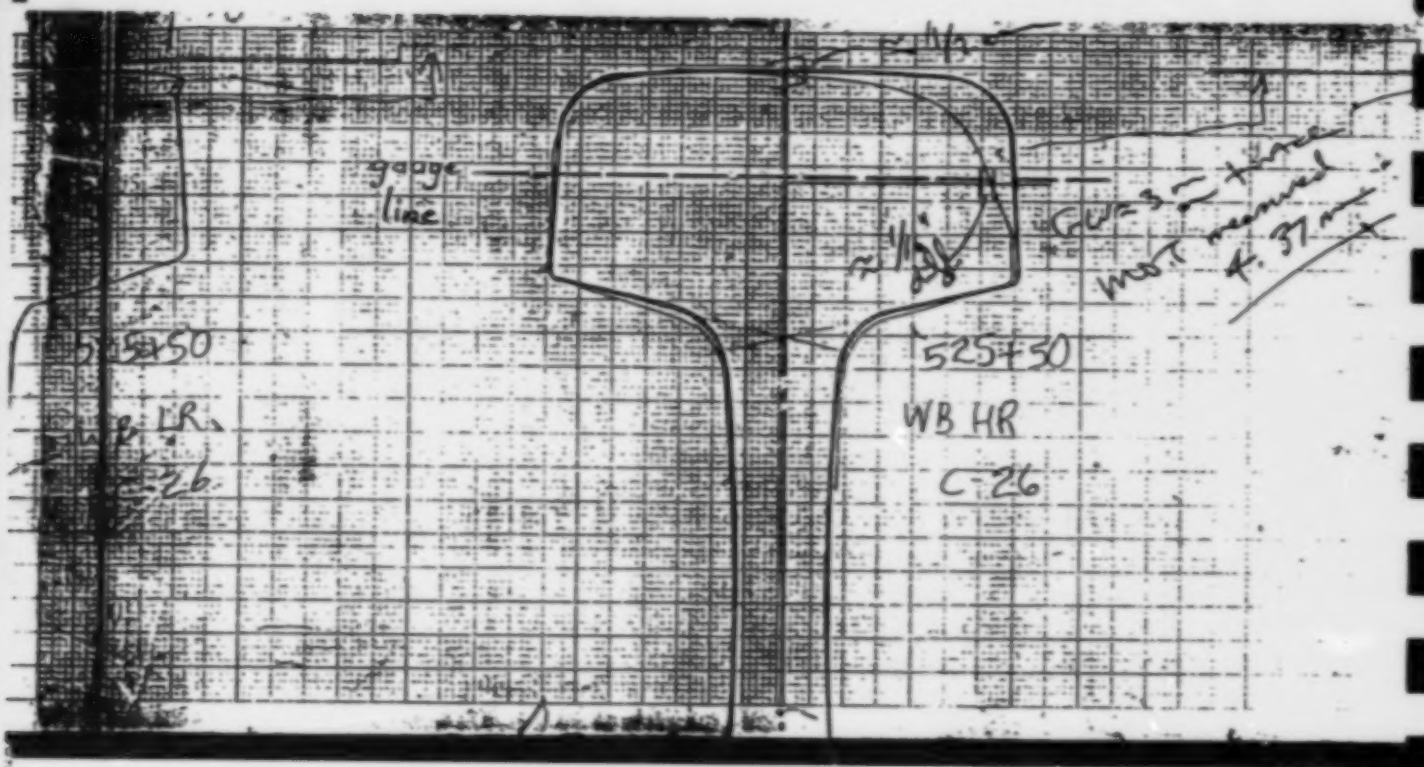

520+50
WB LR
C-26


WB L-R
C-2L


gauge
line


≈3 mm
≈1/8"
gauge
line
524+50
WB HR
C-26


gauge line
GW = 2.5
3.0
525+50
WB HR
C-26
525+50
WB HR
C-26
PJH


gauge line
525+50
WB HR
C-26
525+50
LR
C-26